# Towards Low-Power Everyday Electronic Systems

## Low Power Microelectronics, why and how?

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Although great improvements have been achieved over the years in reducing electrical equipment power consumption, there are indications that we can go a lot further in reducing power levels before we reach any physical limits. Apart from a short history of power reduction, this article describes several interesting and successful projects from the European Initiative in which significantly improved systems with much reduced power levels have been demonstrated.

### What is Power and why is it important in everyday life?

Power is defined in a dictionary as the 'ability to do an operation'. In engineering it is the agent that enables processes and systems to do useful work. Power is the rate of doing work.

In an electronic or microelectronic context electrical power enables those systems to do work; it is measured in a unit called a watt (after the Scottish engineer James Watt (1736-1819)) which is the amount of energy consumed in one second. One watt is a small unit so we often use the unit kilowatt (a thousand watts) — a typical electric fire uses one kilowatt of power for example. We are charged for the electricity we use at home/factory/office by the number of kilowatts we use multiplied by the time in hours, so we are charged for kilowatt-hours. This is energy since it is a product of power and time!

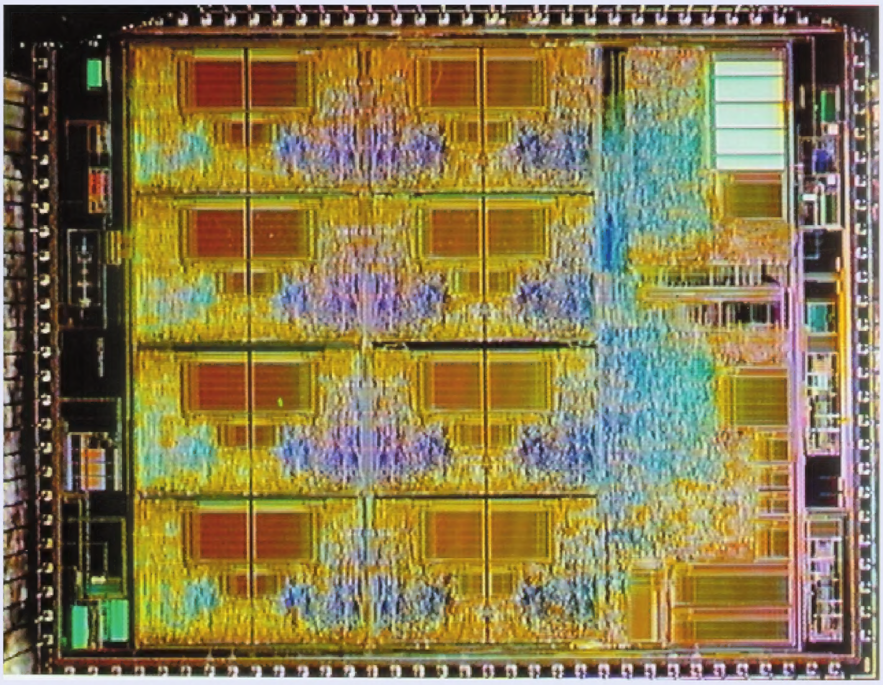
In the UK, the electricity boards charge consumers around 6 pence per kilowatt-hour (or 'units' as they are often referred to on our electricity bills). This then enables us to run the lights/heating and use the multitude of electrical appliances that we all have such as TV, fridge, vacuum cleaner, etc., — the list is endless!

We also have some very important electronic gadgets which we need to use outside the home; in the car, in the street or wherever (so-called portable or mobile systems). I'm thinking here, of course, of mobile telephones, laptop/notebook computers, electronic organisers, as well as more traditional devices such as portable radios/CD players. In the case of these devices plugging into the mains supply may not be appropriate, at least when not close to an electric socket! So, of course, power for these is obtained from batteries, which may be rechargeable from the mains such as Nickel Cadmium (NiCd) batteries or used once and then thrown away e.g. alkaline batteries such as Duracell. Batteries, however, are a very expensive source of power: a typical small battery might have a capacity of say 10 watt-hour (not kilowatt-hour) and cost £2 typically. To obtain one kilowatt-hour would need 100 such batteries at a total cost of £200! When compared with the 6 pence cost of the same amount of electricity from the mains, we can see that electricity from batteries is very expensive. The size and weight of those batteries could also cause a problem!

In conclusion the portability of our modern electronic devices raises issues related to the provision of the power needed to drive those devices which we will now look at in more detail.

## COLOPODS

Cochlear hearing aids use an implant section in the cochlear part of the ear and an external processor and battery. In the current system the external section is rather bulky and has to be carried on the person. The aim is to produce a new device, which can be worn inconspicuously behind the ear. This requires a 50% power reduction overall. The work has concentrated mainly on selecting the optimum Low Power manufacturing process for the chips concerned, increasing system integration, and using novel Low Power techniques in the processor. Early results are encouraging. A photograph of a prototype ear-level unit named COLOPODS is shown in the photograph.



COLOPODS, a design for cochlear hearing implants.

## What is Low Power and why do we need it?

Low Power is a relative and not an absolute measure. It basically means a system that uses less power (by some factor) than required previously in a similar system.

The simple calculation in the previous section showed that the cost of power from batteries is very high compared to power from the mains supply. Clearly therefore, in battery-driven systems, there is a high motivation to develop Low-Power systems on cost grounds alone since the larger the power requirement of the system the larger the battery and therefore its cost.

In addition, if a battery of 1-kilowatt-hour capacity were needed for a particular application we are considering, we would need a battery of a size approaching a car battery but this would clearly be too large and heavy for all hand-held portable equipment.

A more typical battery in terms of size and weight for, say a mobile phone, is the AAA size. Because of its small size, it typically has a capacity of 0.5 watt-hour. This means that if this battery powered-up an electronic system requiring 0.5 watt then after one hour the battery would need changing or recharging. However if the system being driven only required 0.05 watt then the battery would last 10 hours. If the system power consumption was even less at 0.005 watts then we would get 100 hours out of the battery and so on.

So clearly Low Power is also very important in order to extend the operating life of portable equipment between battery changes/recharges as well as weight, size and cost.

The development of the mobile phone over the last 10 years illustrates the need for Low Power very well. Early models were large and bulky (mainly because of the large batteries required), and required battery renewal/recharging almost on a daily basis due mainly to the power-hungry analogue circuitry used in them. They were also costly.

The move to lower power digital models allowed the size of the phones to be reduced due to the smaller, lighter batteries used. Although additional functions were introduced such as message handling, etc, the operating life between battery changes was extended, and the cost of the units dramatically reduced because of the lower manufacturing cost.

The latest models, which have advanced features such as the ability to access the Internet, were designed using Low-Power techniques they are very small and light, have operating life between battery changes up to hundreds of hours or more, and are cheap and affordable to all.

Low Power may also result in a company being able to bring a new application or product to the marketplace, which would have been impossible previously

Finally, Low Power systems have increased reliability since the silicon chips (which are the heart of all electronic systems) run at lower temperatures and are therefore more reliable and we are less likely to get system malfunctions.

Turning now to static systems, such as consumer and various types of electrical equipment, which are powered from the mains supply rather than being battery driven.

It is clear that this type of equipment can also

## LUCS

LUCS embraces the design of a Low Power chip set for a portable Ultrasound application. There is a need for a portable, lightweight, hand-held, ultrasound scanner for medical and veterinary diagnostics. Potential usage in the medical area would be in Urology (for bladder volume, bladder stones, and kidney stones), Obstetrics (foetal age), Abdominal (in emergency, operating theatres, and in military fieldwork). In the veterinary area the unit would be useful for use with pigs, cows, and horses (for pregnancy/fat thickness determinations). The work has concentrated so far on the use of novel Low Power circuits/systems and should result in the production of a demonstrator system by Pie Medical late next year. It is envisaged that the total system power requirement will be reduced by a factor of 3, from the 75 watts of current systems to around 25 watts. The photograph shws an impression of the proposed system.

LUCS is a low power chip designed for use in a portable ultrasound instrument.

benefit greatly from reduced power consumption.

Additional to the advantages already listed for portable systems, static systems have other Low Power considerations of which the more important are the following.

### Cooling and System packaging considerations

Most of the electrical power needed by an electronic system is used inside the system and is converted to heat, which has to be removed by cooling otherwise the sensitive electronic components would overheat and possibly fail. If the system consumes a large amount of power, therefore creating a large amount of heat, special steps have to be taken in the system and component packaging, such as fins and cooling fans, to ensure that the heat is removed effectively. These additional steps add to the system cost and power usage.

We all know how hot a roomful of PCs can get and hence we may also require air-conditioning and other cooling methods to keep the temperature acceptable, again increasing cost.

Low-Power systems need less cooling. This in turn means that the power supply unit required to convert the mains supply into the voltages required to drive the electronic circuit can also be smaller and therefore cheaper.

### Power/frequency considerations

Electronic systems are required to work at higher and higher frequencies (loosely termed speed) in order to give faster operation and higher performance. For instance, today's PC's run at frequencies over 500 MHz whereas only 5 years ago 33 MHz was the norm. The higher the frequency of operation the higher the power will be unless steps are introduced in the design to reduce the power to acceptable levels.

### Effect on the environment

High power consumption and large cooling systems are considered to be bad for the environment in various ways. The US Government has gone as far as stating what the maximum proportion of the National budget that can be spent on power and cooling costs.

Overall then we can see that for reasons of cost, size and weight, long battery operating-life, high-frequency operation, high-reliability, and environmental reasons, Low Power is essential in the design of today's electronic systems.

## How is Low Power achieved?

We will only be able to cover the developments in Low Power very briefly and at a general level in this paper. For a much more detailed description of Low Power we refer the reader to one of the excellent textbooks on the subject. Two such texts are [1,2].

It is generally agreed that Low Power started with the invention of the transistor (the essential building block of electronic systems) in 1947 [3]. The transistor eliminated the need for many watts of power that had been required to power-up vacuum tubes (valves) that had been the basis of electronics up to then. Transistors generally ran at much lower power levels, typically in the tens of milliwatts range (1 milliwatt is one thousandth of a watt). This was further enhanced by the invention of the first Integrated Circuit (silicon chip) in 1958. This enabled the full potential of the transistor to be realised by enabling the whole electronic circuit to be created on a single chip and at lower power levels.

Another significant step was the development of the digital watch in the '70s. This required electronic circuits consisting of several thousands of transistors powered from tiny 'coin cells', the watches had to be physically no larger than traditional watches, and had to operate successfully without a battery change for up to one year. This required the development of Low Power circuits operating at voltages as low as 1.5 V with a power consumption in the microwatt range (1 microwatt is one millionth of a watt). These circuits also found other applications in instrumentation, medical and radio communication.

Since the '70s and particularly with the great demand for portable (or mobile) equipment in the last 15 years, the drive for Low Power has become much more acute. Much work has gone on, world-wide, developing processes, design methodologies and circuit techniques, which have enabled the power consumption of electronic circuits to be reduced by several orders of magnitude.

In order to see, in a little more detail, where and how the improvements have taken place, it is necessary for us to look briefly at the design process for electronic systems.

This process contains many steps but is often split into five main parts for clarity and convenience as follows.

**Overall system level** e.g., mobile phone.

This is the highest level in the design and improvements have been made by planning to place as much as possible of the system (ideally all) on-chip. This is usually referred to as system-on-chip.

**Algorithm level** e.g., the manipulation of two numbers.

At this level power can be reduced dramatically by minimising the number of discrete steps required to carry out computer operations such as addition/subtraction etc.

**Architecture level** e.g. memory blocks such as RAM/ROM.

Measures such as turning off whole blocks of the system when they are not carrying out any useful functions to save power. Analysis shows that, in a computer, many blocks are only used infrequently so significant power saving can be made by turning them off when they are inactive.

This has some parallels with the measure introduced by the carmaker VW in one range of its cars a few years ago. This particular model was marketed as being very good on fuel economy. So circuitry was added to the car to detect when the car was stopped, say at traffic lights, and turn the engine off. When the lights changed the engine quickly started and the car moved off.

Also it is sometimes worth adding additional circuitry to the design to enable the system to optimise its own power usage at any time (power management).

**Logic/circuit level** e.g. a circuit made up of several transistors.

In most digital circuits e.g. computers, the system is controlled by an electronic ‘clock’ circuit which synchronises system performance periodically (synchronous logic). Unfortunately, the clock itself uses a lot of power — often more than the rest of the system!

One option is to design the system without a clock (asynchronous logic) and save power that way. The design procedure however is more complex and may take extra circuitry.

Another option is to use clever circuit techniques to ensure that the circuit switching (which consumes power) is optimised and only takes place when really necessary.

**Device/process level** e.g. individual transistor.

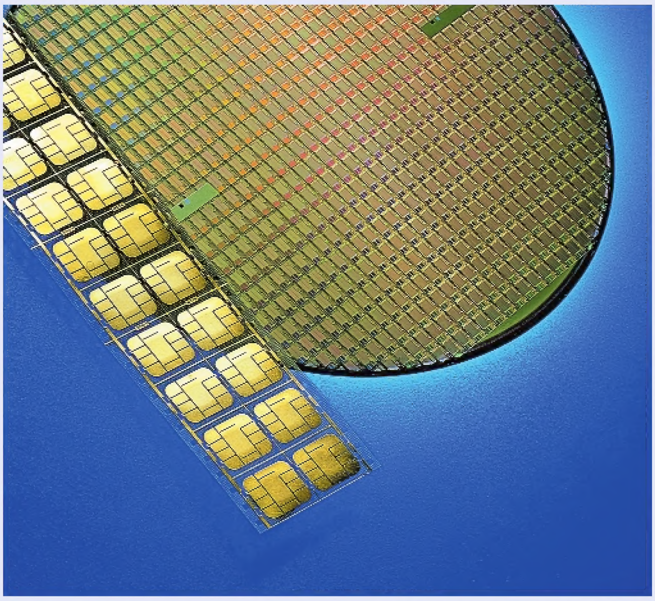
Power is the product of the applied transistor voltage and the resulting transistor current. Hence reducing transistor voltages from, say 5 V, to around 1 V (as was done in digital watches in the ‘70s), reduces power by a factor of 25!

Another major factor here is reducing the physical size of the transistors (scaling). This, not only enables more transistors to be squeezed into a given area of silicon (packing density) but also enables the transistors to consume less power and run at higher frequencies – a win-win situation. Therefore there has been much work in developing microelectronic technology so that smaller and smaller transistors can be made — currently we can make transistors with a minimum size of less than 0.25 micron, compared with 10 micron in 1970 (1 micron is one millionth of a metre). This makes it possible to design complete high performance, low-power, systems-on-chip containing several million transistors in a piece of silicon about 1cm square.

For instance, computers now made in 0.15-micron technology typically use one-third the power of those made in 0.5-micron technol-

## DESCALE

This project is concerned with the design of a Low Power contactless SMART card. SMART cards are used extensively for all kinds of applications e.g. public transport tickets, telephone payment, security etc. currently the sales of these cards are increasing by around 30% per annum. Contactless SMART cards (that work up to 15 cm from the card-reader) have the advantages of convenience, speed-of-use, insensitivity to dirt and grease, and are less susceptible to vandalism. The move to a Low Power version should produce a saving of between 3 and 5 times in power and will save cost, increase applicability and give better security in the cards.



DESCALE is the name of a project aimed at the design of low-power Smartcards.

The work so far has concentrated on the development of an asynchronous system (no clock so the system is only active when needed) whereas the current system is synchronous. This has resulted in new chips being developed which meet the power saving specification (4 times less power required) but with a slight penalty in terms of chip area. This is quite normal with asynchronous systems due to the increased complexity of the design. The photographed working prototype is currently being tested.

ogy and operate at three times higher frequency!

## How much further can we go in reducing Power?

Many papers have been published [3,4] on what are the eventual limits in terms of Low Power. The paper by Meindl [3] is typical. He identified several different limits, each set by a different aspects of microelectronics. We will now briefly consider some of the main ones he listed.

**Fundamental limit**

All microelectronic systems are essentially applications of Physics. Therefore all microelectronic systems obey the laws of Physics and ultimately set the limits of those systems. Meindl concluded that we are currently using around a million times more power in electronic systems than the theoretical minimum so we have plenty more to go at!

**Material limit**

This limit is set by the properties of the silicon itself (or those of its more recent rival Gallium Arsenide). Meindl calculated that we are similarly a long way from any limits on power set by the silicon itself. The limit set by Gallium Arsenide is even further away.

**Device limit**

Most electronic systems are based on the operation of the Field Effect Transistor (FET). By how much more can we reduce its size (and hence the power it uses) before it ceases to behave as a transistor?

Meindl concluded that we could reduce its size by a factor of 4 at least from the current size before we run into trouble on this score. The technology to do this will not be with us until 2010 at the earliest!

Overall therefore his conclusion is that Low Power has plenty room for more reduction.

## The European Low Power Initiative for Electronic System Design (ESDLPD)

In view of the great interest in Low Power, the European Commission set up a major programme in this area in 1997 to run until 2002 with a budget of 14 million Euro. The programme’s aims are to:

- Foster excellence in Low Power design skills,
- Exploit synergy between participants, and
- Transfer know-how and experiences.

Furthermore, the programme’s focus is to:

- Develop advanced methodologies,

## COSAFE

The COSAFE pump is a portable volumetric pump designed to provide long-term infusions associated with cancer chemotherapy, post-operative and chronic pain control, antibiotic infusions and other IV medications. The purpose of the COSAFE project is to develop an easy-to-use infusion pump designed for precision, safety and low power operation, extending operative life between battery changes and minimizing cost. This should also enable the new system to have additional features such as improved user-interface and improved performance.

COSAFE low-power volumetric pump for medical use.

The approach taken is that the current pump, traded under the name RYTHMIC, which is wholly software controlled, will be replaced by a power-minimized partly hardware, partly software co-design system which should give the required power reduction as well as an inherently safe design. The electronic control of the system will be based on a special processor, which incorporates highly safe operation with low power characteristics.

The major power savings of the new pump are achieved by moving the critical, time consuming and thus power consuming, functions of the system from software to hardware and by employing a more sophisticated algorithm for controlling the motor of the pump. The requirement of high safe operation imposes the use of safety mechanisms for controlling every possible failure condition, which may effect the proper operation of the system. These mechanisms for the basic circuit functionality are implemented in hardware (self-checking circuits) aiming at power minimization while the safe execution of the system procedures is ensured by mechanisms implemented in software to increase system functionality. It is estimated that with the followed design approach a reduction in power consumption of around 5 times from the current system will be achieved. The photograph shows the existing pump.

- Adopt best practice for system and application design,
- Research (20% of the resources), and
- Show best practice on demonstrator systems (80% of the resources).

The programme involves 30 of the top companies in the field in Europe together with over 20 well-known Institutes and Universities.

The programme was designated as a 'cluster' which means that the 19 projects (Design Experiments) within the scheme make up a co-ordinated programme of work at all levels of design and is aimed at producing significant improvements in all areas of Low Power microelectronics.

Also, since a major aim of the programme, was to disseminate Low Power design know-how and experiences gained from the programme widely, the Commission insisted that each Design Experiment contained a section aimed specifically at Information Capturing and Dissemination activities (IC & D). Further the Commission appointed the Delft Institute of Microelectronics and Submicron Technology (DIMES) in the Netherlands as the action co-ordinator. The task of the co-ordinator is to co-ordinate, facilitate and organize quality improvements, knowledge sharing and knowledge transfer, from the programme.

In this context many methods are being used to ensure that the information gained from the programme is made available to other interested parties in Europe and elsewhere.

Networking is carried out through regular meetings of the two Interest Groups, one in the Digital area and one in RF/Analogue.

Results are gathered, based on the reports written by the Design Experiments and published in books of several types, journals and magazines, as well as, in the future, on a Low Power Design web server.

Additionally course material, design kits and tools are being produced; and special sessions held at major European Conferences comprising workshops and tutorials.

For further information on the IC & D activity please contact DIMES on (+31) (0)15278 6696 or access the ESDLPD website on http://www.esdlpd.dimes.tudelft.nl

## Output to date

The programme has been in operation since 1997 and several of the Design Experiments (which are all of 2-3 years duration) have finished or will finish shortly.

They are producing demonstrator outputs, which have impressive reductions in power over current systems and other advantages. A cross-section of the more interesting ones is shown in the insets in this article.

## Conclusions

This article has attempted to describe the topic of power to the reader and its importance in everyday life. Further it has described why Low Power is important and how we can obtain systems operating at much reduced levels of power. Additionally it has detailed improvements made over the years but indicates that we can go a lot further in reducing power levels before we reach any physical limits.

The article then describes a successful, major European Commission initiative in this area and particularly how it disseminates the knowledge gained from that programme widely.

Finally the article describes several interesting and successful projects from the European Initiative in which significantly improved systems with much reduced power levels have been demonstrated.

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## References

1. A Bellaouar and M I Elmasry.
'Low Power Digital VLSI Design',
Kluwer Academic, 1995, ISBN 0 7923 95 87 5.
2. Gerson A S Machado (Editor).
'Low Power HF Microelectronics – a unified approach'.
IEE, 1996, ISBN 08529 6874 4.
3. James D. Meindl,
'Low Power Microelectronics: Retrospect and Prospect'
Proceedings of the IEEE Vol 83, No 4, pp619-635, April 1995.
4. E. A. Vittoz,
'Low Power Design: ways to approach the Limits',
Plenary address ISSCC '94 San Francisco, February 16-18 1994.
5. Presentations at the ESD-LPD Open Workshop, Como, Italy, March 3rd 1999
6. Report of the Processor and Algorithms Special Interest Group meeting, Schiphol, Netherlands, Nov 23 -24 1998